AD-A017 183

COMPUTER ERROR ANALYSIS OF TROPOSPHERIC EFFECTS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

John R. Schmidt, III

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

January 1975

PII Redacted

AD [illegible]

AIR FORCE INSTITUTE OF TECHNOLOGY

AIR UNIVERSITY
UNITED STATES AIR FORCE

SCHOOL OF ENGINEERING

Copy available to DDC does not
permit fully legible reproduction

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

INSTRUCTIONS
BE COMPLETING FORM

1. REPORT NUMBER
GE/EE/75-7

2. GOVT ACCESSION NO.

3. RECIPI CATALOG NUMBER

4. TITLE (and Subtitle)
COMPUTER ERROR ANALYSIS OF TROPOSPHERIC EFFECTS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

5. TYPE OF REPORT & PERIOD COVERED
MS Thesis

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
John R. Schmidt III
Captain USAF

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Air Force Institute of Technology(AFIT-EN)
Wright-Patterson AFB, Ohio 45433

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Advanced TRACALS Division (XPIN)
Air Force Communications Service
Richards-Gebaur AFB, Missouri 64030

12. REPORT DATE
January, 1975

13. NUMBER OF PAGES
73

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Approved for public release; IAW AFR 190-17
JERRY C. HIX, Captain, USAF
Director of Information

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Satellite Navigation
Troposphere
NAVSTAR Global Positioning System

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computer program was written to calculate the tropospheric induced position error variances associated with the NAVSTAR Global Positioning System. The steps were outlined leading to the mathematical relations necessary for transforming position coordinates and for calculating the direction cosine angles of the user-to-satellite vector relative to a coordinate system placed on the user. Random variables were introduced to analyze the error asso-

ciated with the user-to-satellite range determination.

A comprehensive reference source listing was compiled on satellite navigation systems studied by the United States Army, Navy, and Air Force, air traffic control employing navigation satellites, tropospheric effects on passive ranging, and the effects of multipath and noise on passive ranging.

The appendices to this thesis include the computer program listing and a listing of all computer language useage not conforming with USA standard fortran as defined in standard USAS X3.9-1966, of the American National Standards Institute, Inc.

1

COMPUTER ERROR ANALYSIS OF TROPOSPHERIC EFFECTS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

THESIS

GE/EE/75-7

John R. Schmidt III
Captain USAF

Approved for public release; distribution unlimited.

COMPUTER ERROR ANALYSIS OF TROPOSPHERIC EFFECTS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

John R. Schmidt III, B.S.E.E.
Captain USAF

Graduate Electrical Engineering
March 1975

Approved for public release, distribution unlimited.

Preface

This thesis was prepared at the request of Air Force Communications Service (AFCS), XPIN, Richards-Gebaur Air Force Base, Missouri. Researchers are studying the feasibility of a satellite system for precise navigation in the post-1980 time frame. As a result, AFCS has been tasked with studying the proposed NAVSTAR Global Positioning System, and for this reason, I have written this paper with a two-fold purpose. First, I have researched and compiled an extensive reference source listing of current and past information concerning satellite navigation systems, the troposphere, multipath, and noise. Finally, I wrote a computer program to predict position errors that might result from the tropospheric effects on passive ranging from a high altitude satellite navigation system.

I would like to thank Dr. E. C. Altshuler, Air Force Cambridge Research Laboratory, for his time and assistance in leading me through the literature dealing with tropospheric modeling.

I would also like to express my gratitude to Major R. A. Reinman, Air Force Institute of Technology, for his scrutinizing guidance throughout my preparation of this thesis.

JBS

Contents

List of Figures

Abstract

A model for tropospheric delay of a radio signal from a satellite, developed by E. Altshuler of the Air Force Cambridge Research Laboratory is used to perform a three-dimensional tropospheric error analysis for the NAVSTAR Global Positioning System (GPS). A program to evaluate the error as a function of satellite positions and elevations, user altitude, and surface index of refraction is developed. It is found that the order of magnitude of the tropospheric errors is such that these errors are not an impediment to possible aircraft precision approaches using NAVSTAR. An extensive bibliography of NAVSTAR and satellite navigation literature is included.

COMPUTER ERROR ANALYSIS OF TROPOSPHERIC EFFECTS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

I. Introduction

Background for NAVSTAR

Scientists, engineers, and planners have recently been tasked with seriously studying currently available navigation systems in an effort to devise a futuristic system capable of meeting the requirements of the United States after 1980. Prior to 1973, the Air Force and the Navy actively and independently pursued the idea of position determination and navigation using satellites. TRANSIT is a result of Naval Air Systems Command research and development and has a limited operational capability as a navigation satellite system (Ref 7). Another major effort by the Navy, TIMATION (Time Navigation), provided valuable information about space-based oscillators for time referencing (Ref 5:1). The Air Force System 621B revealed the feasibility of highly accurate three-dimensional navigation with radio signals from satellites. The results of system 621B testing at Holloman Air Force Base and the White Sands Missile Range convinced planners that a space-based navigation system also provided sufficient accuracy for potential use as an advanced air traffic control system and as a precision instrument approach aid (Ref 8:2).

In order to integrate the previously independent efforts of the Air Force and the Navy, the Deputy Secretary of Defense issued a memorandum in April 1973 naming the Air Force as the executive service for the future Defense Navigation Satellite System (DNSS), designated NAVSTAR Global Positioning System (GPS) (Ref 10: Chap. I, pp. 1-2). Ultimately, the NAVSTAR system will be composed of three high-altitude orbits containing eight satellites each. Each orbit will be elevated 63° from the equatorial plane and spaced 120° about a pole-to-pole reference axis from adjacent orbits as shown in Fig. 1.

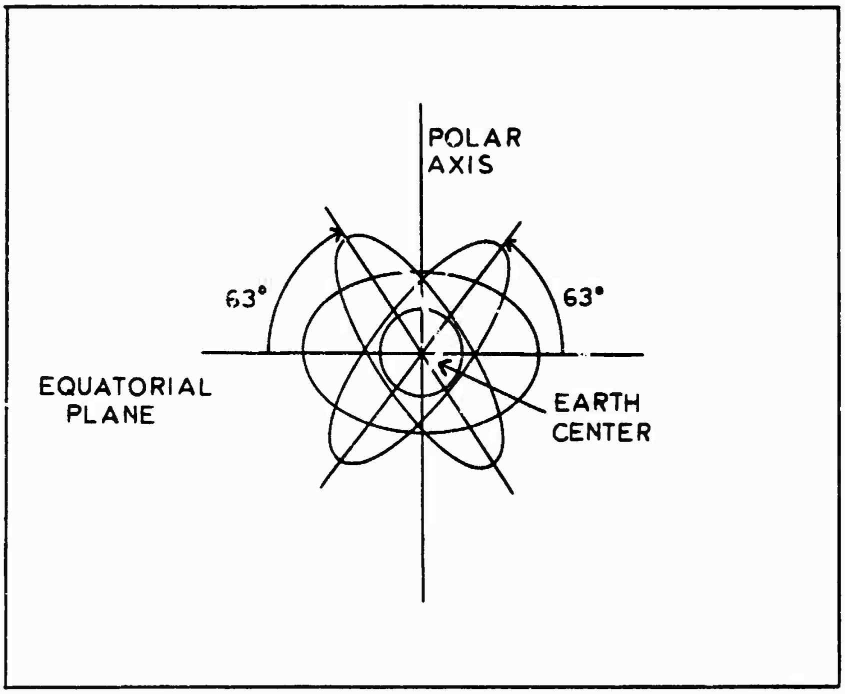

Fig. 1. Orbital Configuration

Maximum utilization of the system will be obtained by interpretation of range and clock bias information from four satellites visible to the user. Position determination requires analysis of range information from three of the satellites. The user then calculates the signal delay time resulting from tropospheric diffraction and refraction, and converts this delay into a range error, ΔR, associated with each satellite. These range errors are then used to calculate the "approximate" user-to-satellite ranges. The NAVSTAR geometry is depicted in Fig. 2. With such a versatile system for worldwide position determination (keeping in mind both states of national emergency and peacetime), there is a need for knowledge of how accurate the position prediction will be.

Problem Definition

The problem addressed in this thesis is the analysis of range information as it is perturbed by the troposphere. Specifically, a computer program is developed which will apply the tropospheric model developed by Altshuler (Ref 1) to the range information from three satellites. The range information will be used to calculate the user's position and variances associated with each of the position parameters. Additionally, the computer program will provide a capability for determining the user's position variances as a function of satellite positions. Finally, this thesis will include an extensive reference source listing covering satellite navigation, effects of multipath and noise, tropospheric effects, and air traffic control with navigation satellites.

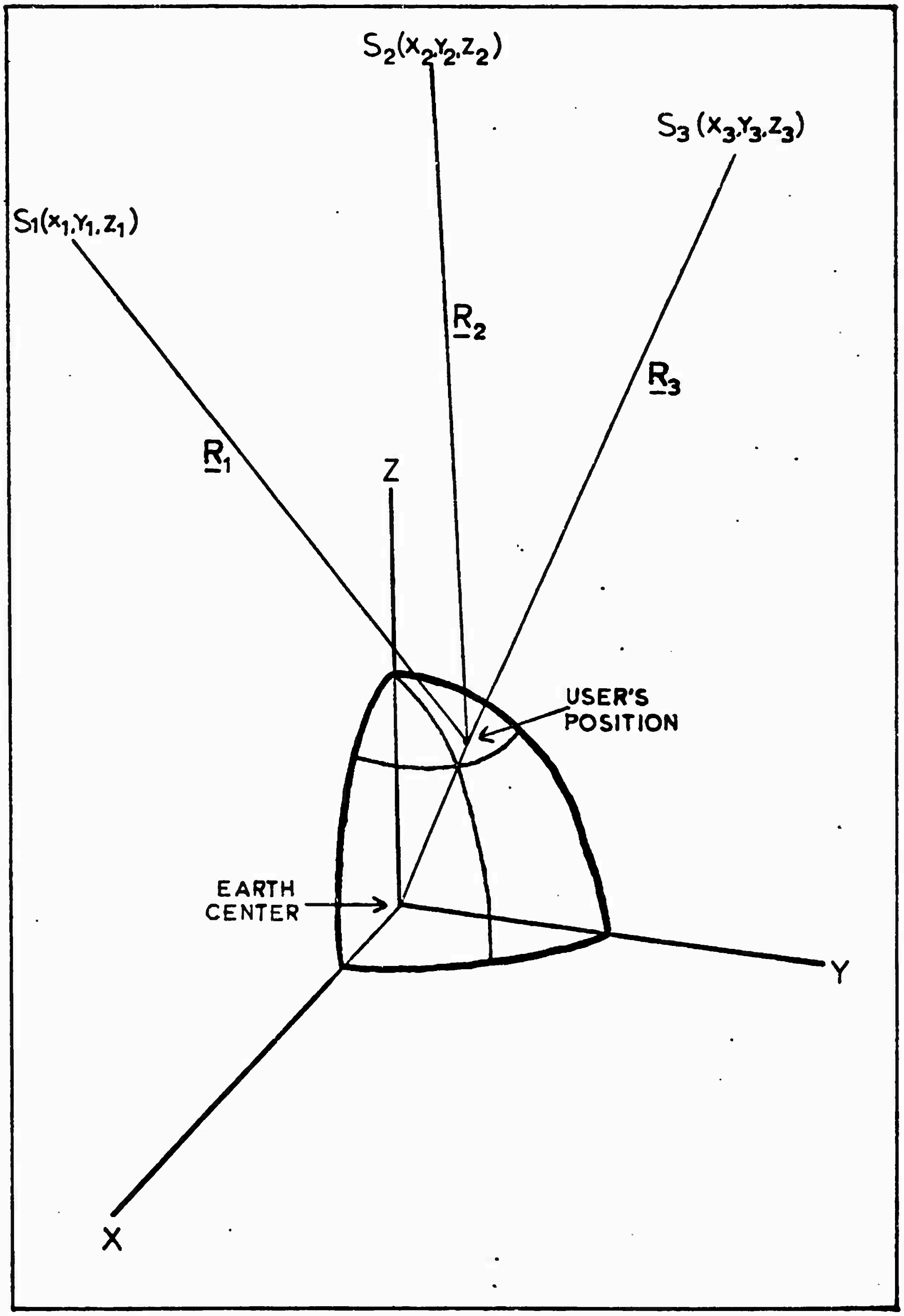

Fig. 2. Typical NAVSTAR Geometry

Scope

In NAVSTAR, user position determination and the associated errors are a function of satellite position, tropospheric refraction, noise, and the effects of multipath propagation. Since current technology provides the capability of predicting a satellite's position within a few feet (Ref 4:440), satellite position error will not be considered in this paper. The position error resulting from receiver noise will be unique to the user's receiver and as such, calibration or compensation for the characteristics of a specific receiver should minimize this error source. Thus, the effects of noise will not be considered in this paper. Multipath will probably be a major concern to planners, especially for low satellite elevation angles and low altitudes. Since this error is geography-dependent, separate consideration is required in any region, and thus its effects will not be considered here. The scope of this paper will therefore include only the effects of tropospheric refraction and signal delay on the range information from each of three satellites.

Assumptions

The mathematics required to solve for position variances is a direct application of the developments by E. C. Altshuler, Cambridge Research Laboratories, to a three-satellite system (Ref 1 and Ref 2). The assumptions made by Altshuler are also assumed in this paper.

To obtain an approximate user altitude, which is necessary for calculating range error, the radius of the earth is assumed to vary linearly from the poles to the equator. In the operational NAVSTAR system, actual sea level information will be extrapolated between precisely surveyed monitor stations.

It is assumed the satellite ephemeris (position) error is insignificant although it may become necessary to account for this error at a later date. The GPS Specifications list the standard deviation of ephemeris error as 1.6 feet, much smaller than the radius of the satellite and accompanying antennas (Ref 11:8).

Finally, it is assumed that the three random variables representing the user's range from each of the satellites are statistically independent since the clocks aboard the satellites are mutually independent.

II. Mathematical Derivations Necessary for Computer Implementation

In this chapter we will develop the necessary mathematical relations for integrating the work done by Altshuler into a three satellite system. First, we will show the steps required to solve for the intersection of three overlapping spheres. Next, we will develop the direction cosine angles for the user-to-satellite vector and specialized orthogonal axis system centered on the user. Finally, we will develop position variances in components corresponding to the user-centered axis system.

Position Solution

The user's position is basically determined by the intersection of three spheres represented by three quadratic equations:

$$(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2 = R_1^2 \qquad (1)$$

$$(X - X_2)^2 + (Y - Y_2)^2 + (Z - Z_2)^2 = R_2^2 \qquad (2)$$

$$(X - X_3)^2 + (Y - Y_3)^2 + (Z - Z_3)^2 = R_3^2 \qquad (3)$$

where

X_n, Y_n, Z_n $(n = 1,2,3)$ = The satellite coordinates in a geocentric system

R_n $(n = 1,2,3)$ = The radii of the spheres representing the range to the satellite from the user.

After expanding the quadratic terms and collecting like-ordered terms, Eqns. (1), (2), and (3) become

$$X^2 + K_{11}X + Y^2 + K_{12}Y + Z^2 + K_{13}Z = K_1 \tag{4}$$

$$X^2 + K_{21}X + Y^2 + K_{22}Y + Z^2 + K_{23}Z = K_2 \tag{5}$$

$$X^2 + K_{31}X + Y^2 + K_{32}Y + Z^2 + K_{33}Z = K_3. \tag{6}$$

We now have three quadratic equations in three unknowns, and by using parametric equations, we will be able to determine the points common to the three spheres (three overlapping spheres intersect in two points).

To develop the appropriate parametric equations, we must first find the planes of intersection of two pairs of the spheres. This results in two first order equations, found by subtracting Eqns. (5) and (6) from Eqn. (4).

$$C_{11}X + C_{12}Y + C_{13}Z = C_1 \tag{7}$$

$$C_{21}X + C_{22}Y + C_{23}Z = C_2. \tag{8}$$

The parametric equations then follow

$$X = Nt + X' \tag{9}$$

$$Y = Ot + Y' \tag{10}$$

$$Z = Pt + Z' \tag{11}$$

where X',Y', and Z' = any point on the line common to the intersection of the planes represented by Eqns. (7) and (8)

N,O, and P = coefficients of the cross product of the normals to the planes represented by Eqns. (7) and (8) (Ref 12:625).

Substitution of the parametric equations into Eqns. (1), (2), or (3) yields a quadratic equation in terms of the parameter t. Once the two solutions of this equation are determined, they can be substituted in turn into Eqns. (9), (10), and (11) to determine the two points common to the intersection

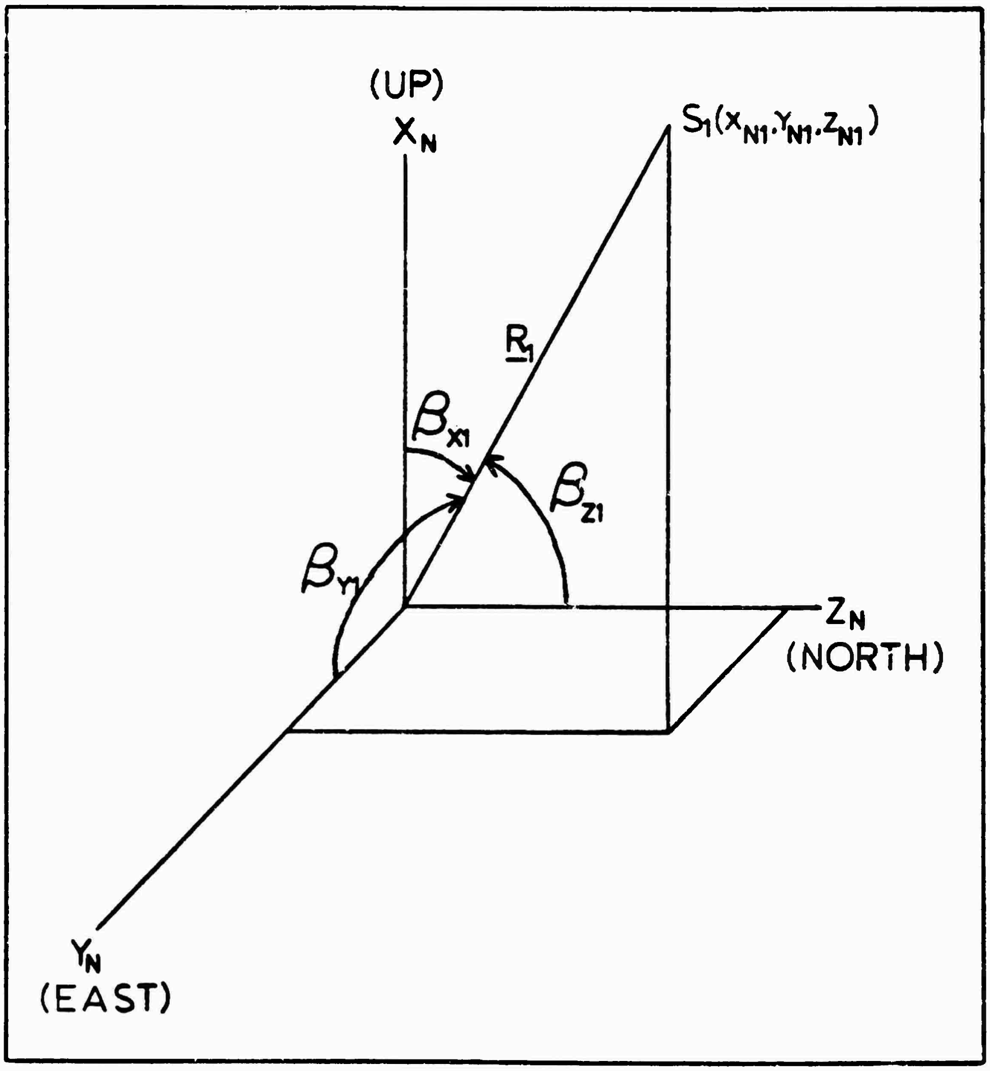

Fig. 3. Results of Axis System Rotated and Translated to the User

NOTE - Only one satellite is depicted with its respective direction cosine angles.

of the three spheres represented by Eqns. (1), (2), and (3) (Ref 3:170-173).

Calculation of Direction Cosine Angles

In order to calculate variances of the estimate of the user's position, we will first center an orthogonal axis system on the user with axes aligned to the up (altitude) direction, East, and North as depicted in Fig. 3. To insure validity in all octants, we will define all positive angles with standard directions in right-handed coordinate systems. We can now define a point (x,y,z) in the geocentric coordinate system as a new point (x_N, y_N, z_N) in a user-centered coordinate system by an axis rotation about the Z axis (Fig. 4.) followed by another rotation about the displaced Y axis (Fig. 5.), and a translation to the user along the displaced X axis. The parameters (ρ, θ, ϕ) correspond to the polar coordinates of the user's geocentric position and the required axis rotations and translation necessary to place a new coordinate system on the user.

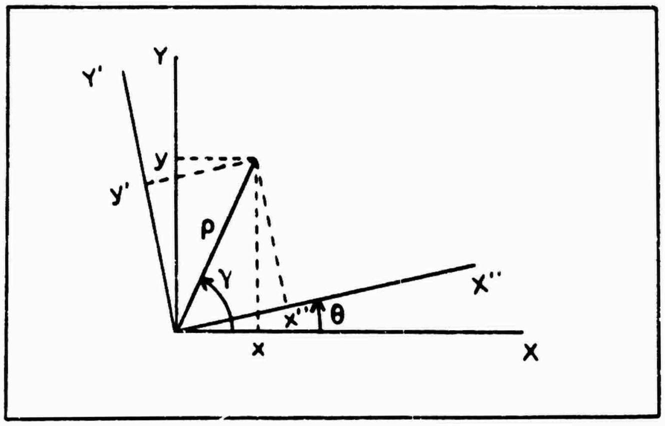

Fig. 4. Axis Rotation in X-Y Plane

The value for x and y in the geocentric coordinate system are represented by Eqns. (12) and (13) (Ref Fig. 4).

$$x = \rho\cos(\gamma) \tag{12}$$

$$y = \rho\sin(\gamma). \tag{13}$$

The same point, in the new axis system, rotated an angle θ about the Z axis is

$$x'' = \rho\cos(\gamma-\theta) \tag{14}$$

$$y' = \rho\sin(\gamma-\theta) \tag{15}$$

or

$$x'' = x\cos(\theta) + y\sin(\theta) \tag{16}$$

$$y' = -x\sin(\theta) + y\cos(\theta). \tag{17}$$

with these values, we can rotate the axis system about the Y' axis an angle ϕ as shown in Fig. 5. With the same logic and a trigonometric identity, we calculate the remaining values of the point in the new rotated system

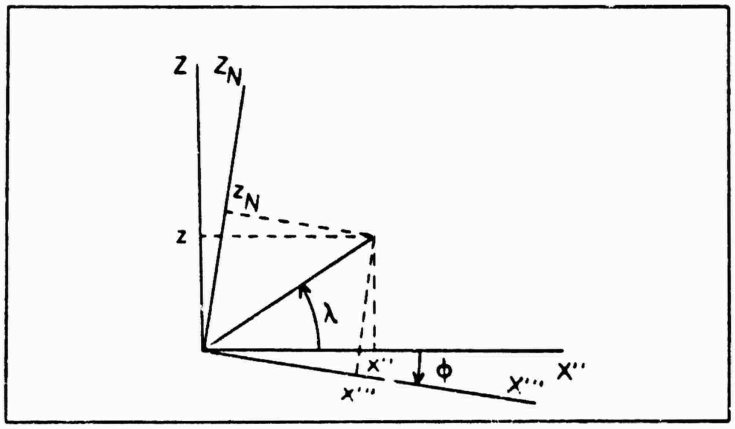

Fig. 5. Axis Rotation About the Y' Axis

$$x''' = -z\sin(\phi) - (x\cos(\theta) + y\sin(\theta))\cos(\phi) \tag{18}$$

$$z_N = z\cos(\phi) - (x\cos(\theta) + y\sin(\theta))\sin(\phi). \tag{19}$$

Since the X''' axis lies along the vector to the user's position, a translation out this axis a length ρ yields

$$x_N = -z\sin(\phi) - (x\cos(\theta) + y\sin(\theta))\cos(\phi) - \rho \qquad (20)$$

$$y_N = y\cos(\theta) - x\sin(\theta) \qquad (21)$$

$$z_N = z\cos(\phi) - (x\cos(\theta) + y\sin(\theta))\sin(\phi) \qquad (22)$$

(Ref 3:168).

By knowing the geocentric coordinates of the three satellites, we can calculate the direction cosine angles of the user-to-satellite vector ρ_N relative to the user-centered axis system

$$\beta_x = \cos^{-1}(x_N/\ \rho_N\ ) \qquad (23)$$

$$\beta_y = \cos^{-1}(y_N/\ \rho_N\ ) \qquad (24)$$

$$\beta_z = \cos^{-1}(z_N/\ \rho_N\ ). \qquad (25)$$

Calculation of Variance

Since we are assuming the error, ΔR, is actually along the vector from the user to each satellite, we can now use the direction cosine angles to find the components of the error along each of the axes at the user. For example, we will consider the altitude error

$$E_H = E_1\cos(\beta_{x1}) + E_2\cos(\beta_{x2}) + E_3\cos(\beta_{x3}) \qquad (26)$$

where

E_i (i = 1,2,3) = error associated with each satellite

β_{xi} (i = 1,2,3) = direction cosine angles between the user-to-satellite vector and the axis corresponding with altitude.

Since we are considering the error to be a random variable and we are assuming the three random variables to be independent and the error distributions to be gaussian, we will add the corresponding variances, giving us an altitude variance

$$V_H = (\sigma_1 \cos\beta_{x1})^2 + (\sigma_2 \cos\beta_{x2})^2 + (\sigma_3 \cos\beta_{x3})^2 \qquad (27)$$

where

σ_i $(i = 1,2,3)$ = standard deviation of the range error associated with each satellite (Ref 9: 250-251).

Using the same logic, east-west variance and north-south variance are

$$V_E = (\sigma_1 \cos\beta_{y1})^2 + (\sigma_2 \cos\beta_{y2})^2 + (\sigma_3 \cos\beta_{y3})^2 \qquad (28)$$

$$V_N = (\sigma_1 \cos\beta_{z1})^2 + (\sigma_2 \cos\beta_{z2})^2 + (\sigma_3 \cos\beta_{z3})^2 \qquad (29)$$

We have introduced the mathematical relations necessary for calculating position variances by a passive ranging technique from high altitude navigation satellites. We first outlined the steps for determining the points common to three overlapping spheres in an orthogonal, right-handed axis system. Next, we outlined the steps for the rotation and translation of an orthogonal axis system. We then combined these developments to derive the direction cosine angles of a known vector relative to the new axis system. Finally, we introduced random variables and developed variances relative to the new axis system.

III. Computer Program

As a part of this thesis, a computer program was written to calculate position variances resulting from tropospheric effects on passive ranging. This chapter will discuss the purpose of each subroutine and the versatility of the complete program.

Explanation of the Subroutines

The computer program is composed of eight subroutines, each with a specific function, supporting a main program which can provide any of three output options shown in the flowchart in Fig. 6.

DRCSNS (direction cosine angles). This subroutine requires that the calling program provide satellite coordinates and the user's geocentric position. It then calculates the direction cosine angles of the user-to-satellite vector relative to an orthogonal axis system at the user with axes corresponding to up (altitude), East, and North. In addition, this subroutine converts earth-centered satellite coordinates to user-centered coordinates.

DELTAR (ΔR). The arguments required to call this subroutine are user altitude, satellite elevation angles, and index of refraction. This subroutine then calculates the predicted tropospheric range error of the user from each of the three satellites. The tropospheric model was developed by Altshuler (Ref 1).

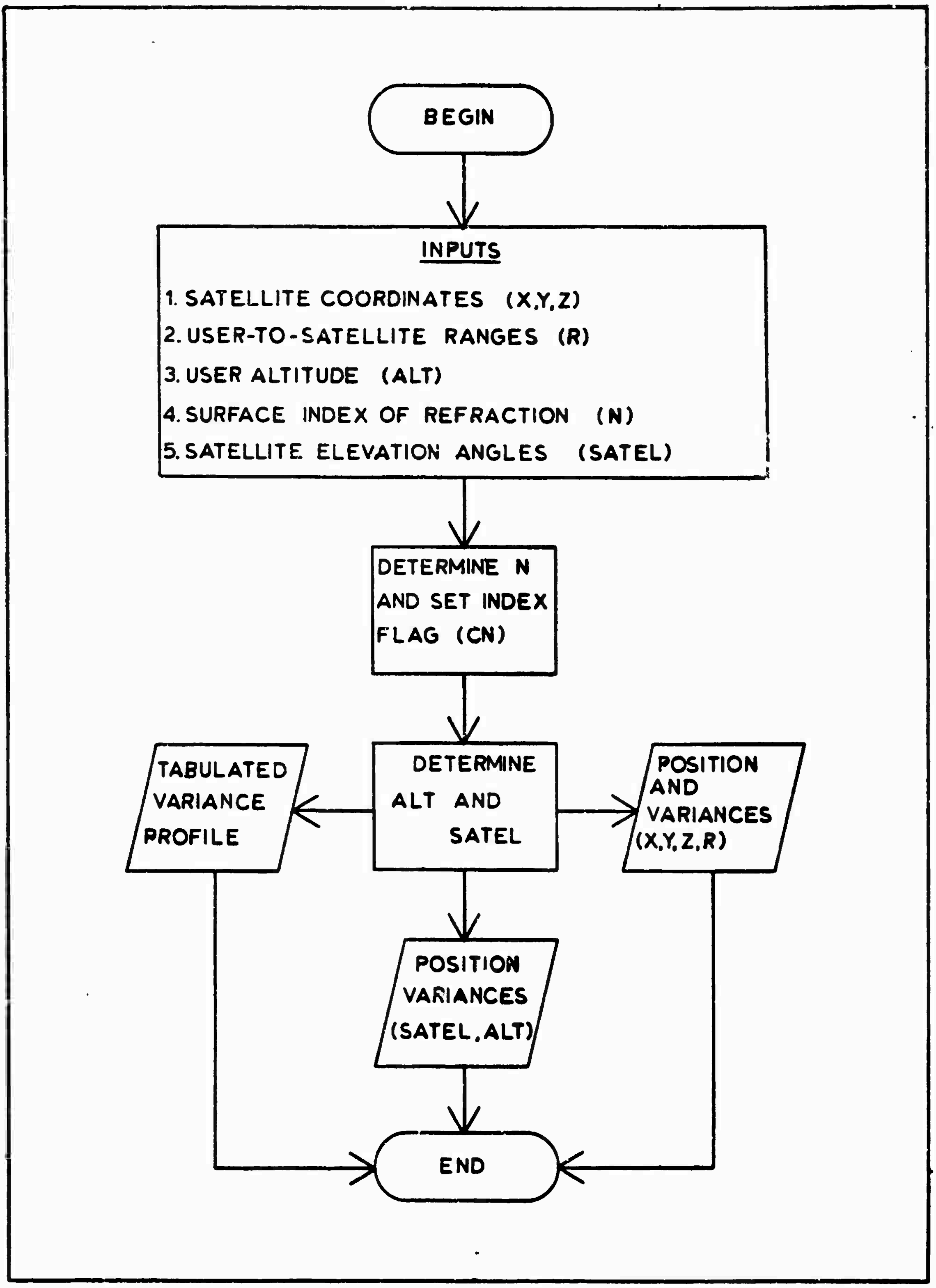

Fig. 6. NAVSTAR Computer Program Flowchart

VAR (variance). This subroutine calculates the user's altitude position variance, east-west position variance, and north-south position variance from the direction cosine angles, range error, and the index of refraction flag (which tells the subroutine if the index of refraction was known precisely or estimated). The necessary calculations are based on the linear relation between standard deviation and range error developed by Altshuler (Ref 2:11).

ALTEST (altitude estimator). This subroutine estimates altitude and satellite elevation angles from satellite positions and user-to-satellite range information, if these parameters are not initially specified. This subroutine is used primarily for problem simulation and program verification because altitude and satellite elevation angles should be precisely known in actual system utilization. A modification of this subroutine could be used as a back-up for determining satellite elevation angles and altitude in the event of on-board equipment failure.

PTOR (polar to rectangular). This subroutine is used to convert polar coordinates to rectangular coordinates. If the satellite positions are provided in rectangular coordinates, this subroutine may be eliminated.

PSN (position). This subroutine is used to solve the three simultaneous second order equations representing three spheres, whose radii are R_i and which are centered on the satellites at (X_i, Y_i, Z_i), $i = 1,2,3$. Since the solution involves two points, this subroutine selects the correct point by comparing the given user altitude with the altitudes computed from the two points. This approach breaks down if all three satellites are in the same plane with the earth since both points yield the same altitude, but because of the problem geometry, this condition would be of short duration and could be disregarded. In actuality, the NAVSTAR system will rely on range information from the fourth satellite to select the correct point. The solution is provided to the main program in both polar and rectangular coordinates.

VARPROF (variance profile). The output from this subroutine is a comprehensive tabulated position variance profile dependent upon altitude, index of refraction, satellite elevation angles, and the angle of rotation from north of the plane defined by the XN axis and each satellite. The calling program must specify altitude, index of refraction, and the refractive index flag. All angular iterations in this subroutine are with respect to the user-centered axis system and the increments and starting points may be adjusted by the operator.

VNCE (variance). This subroutine allows the planner to calculate position variances for one specific combination of satellite elevation angles, angles between north and the plane defined by the XN axis and each satellite, user altitude, surface index of refraction, and the refractive index flag.

Program Versatility

Output Variations. The computer program is designed to provide three specific output formats as shown in Appendix A.

The first format is a typical user position solution and associated variances given the position of three satellites and respective user-to-satellite range information. The second format shows the tabulated output obtained from the VARPROF subroutine. By setting the angular interation increments in the six "do" loops and specifying altitude, surface index of refraction, and the refractive index flag, the planner can list the position variances for any possible combination of three satellites. The third format lists the position variances for any selected combination of three satellites.

The computer program is structured to provide the planner with a versatile tool for predicting position variances resulting from tropospheric effects. In addition, modifications of the basic program can result in a variety of outputs such as the results depicted in the graphs shown in Figs. 7 and 8. Because of the range of the satellites from the center of the earth, satellite elevation angle is practically invariant as user altitude varies between sea level and 60,000 feet. (For example, at low satellite elevation angles these elevation angles change about .05° between sea level and 60,000 feet.) By eliminating the six "do" loops associated with satellite angles and by fixing these values, we can design our output to show the relation between position variances and altitude.

System-Program Compatibility. The computer program was designed for use on the CDC 6600 system using Fortran IV

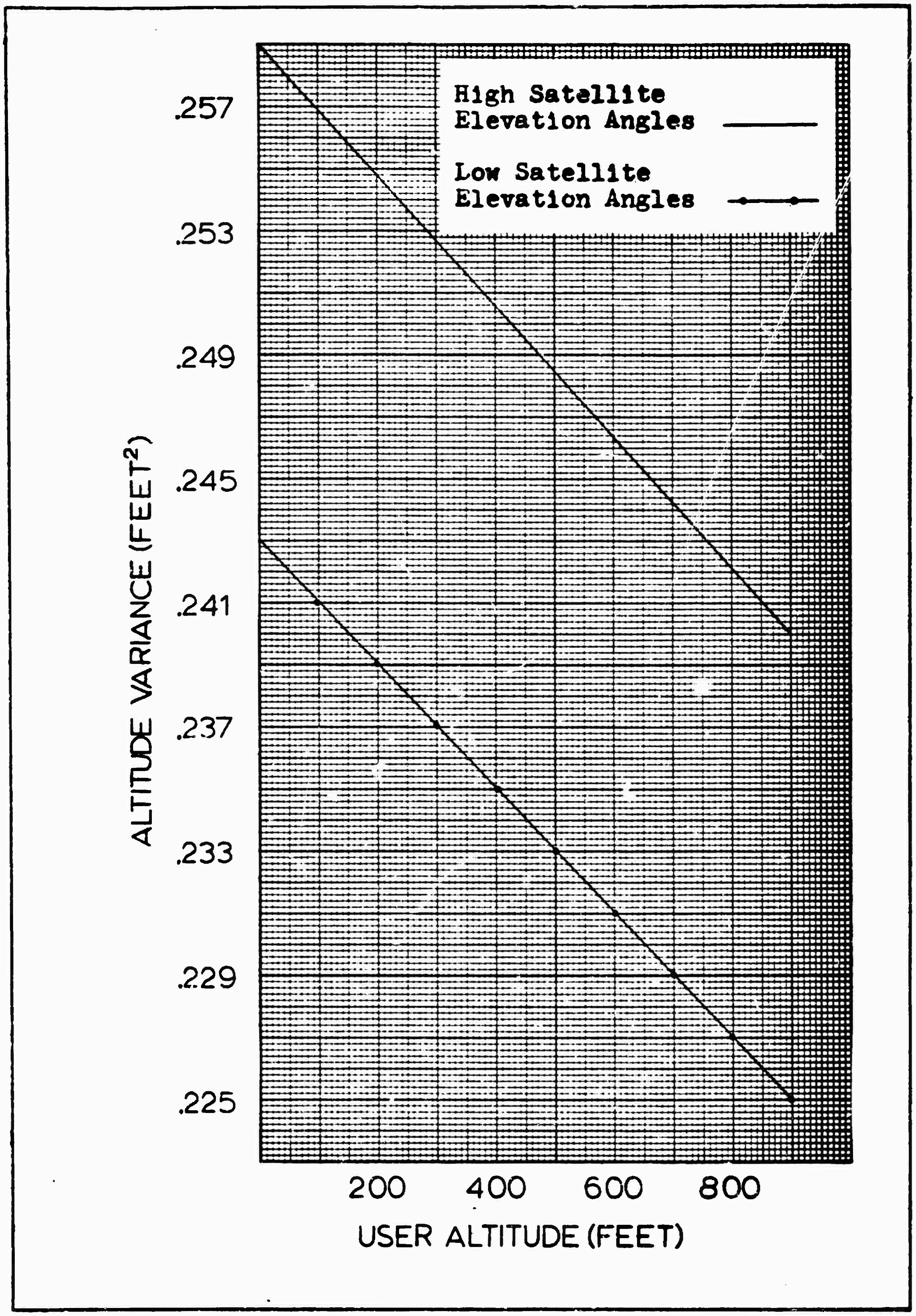

Fig. 7. Altitude Variance vs. Altitude

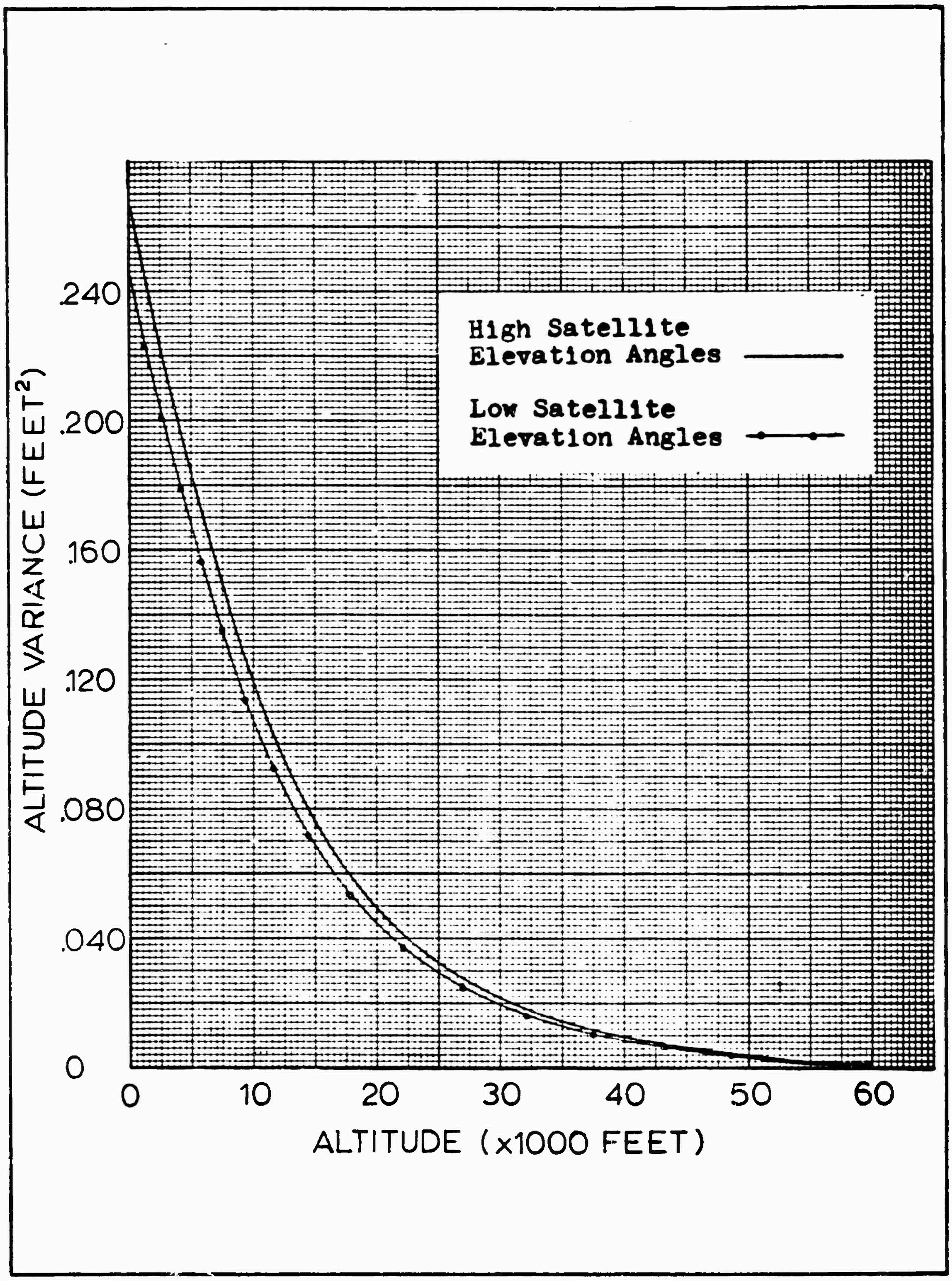

Fig. 8. Altitude Variance vs. Altitude

source language (Appendix B). A list of all non-ANSI (American National Standards Institute) language useage (Appendix C) is provided for converting the program, if necessary, to be compatible with some other computer system.

IV. Literature Search Results

This chapter contains a listing of reports containing information pertinent to the understanding of NAVSTAR. Reports are listed under the following major subject areas; Air Force 621B Satellite Navigation System, Air Traffic Control Employing Satellites, The Troposphere and Satellite Navigation, Multipath, NAVSTAR GPS, and Miscellaneous Reports Associated with Satellite Navigation. Where possible, the listing includes a brief description of the report. Defense Documentation Center reference numbers are included when available.

Air Force 621B Satellite Navigation System

1. FLIGHT TEST OF THE 621B NAVSAT SYSTEM, by B. O. Montgomery, P. G. Howe, and C. E. Hymas. January 1973. (AD-967 451L)*

This report contains the results of testing two navigation receivers to evaluate system performance and identify inherent problems of the 621B Navigation Satellite System.

2. SYSTEM 621B USER EQUIPMENT DEFINITION AND EXPERIMENTS PROGRAM, by J. J. Courtney, R. Laho, and I. Kadar. April 1973.

This report, in three volumes, summarizes a series of flight and ground tests, conducted at the White Sands Missile Range, to evaluate the performance of user equipment in flight and field environments.

---

*DDC numbers followed by an L are limited documents. These are available only through a technical justification acceptable to the contracting authority.

VOLUME 1 (AD-910 451L) - This is a summarized description of the 621B program, the ground and flight equipment, and an overview of the test results.

VOLUME 2 (AD-910 452L) - This paper discusses program history, equipment description, and data processing approach.

VOLUME 3, part 1 (AD-910 453L) and part 2 (AD-910 454L) - These papers offer a detailed presentation of the data taken during the program and a discussion of the results and conclusions to be drawn. Much of the technology from the Air Force 621B program carried over directly to the NAVSTAR program.

Air Traffic Control Employing Satellites

3. STUDY OF A NAVIGATION AND TRAFFIC CONTROL TECHNIQUE EMPLOYING SATELLITES.

VOLUME 1, by D. D. Otten. December 1967 (N68-31277; TRW-08710-6012-R000, V-1). - User hardware, satellites, and ground stations were considered for use in a navigation and traffic control system for Atlantic coverage for large aircraft, general aviation aircraft, and marine craft. An error analysis was made of all operation modes, critical test areas were defined, and rates and capacity of the system for traffic control were determined. Estimates were made for costs of hardware making up the navigation subsystem of the satellite and the ground station network, as well as for hardware costs to various classes of users. Modulation techniques for ranging were studied, breadboards of several antenna designs were tested, and an industry survey of user state-of-the art was made.

VOLUME 2, by D. A. Conrad. December 1967 (N68-31278; TRW-08710-6012-R000, V-2). - Satellite constellation and ground station network analyses are documented, and the results of tracking accuracy and error analyses are presented. Measurement correlations are identified as time-serial correlation, interstation correlation, and intersatellite correlation. Overall navigation accuracy is analyzed for the complete worldwide system and for an interim system covering the North Atlantic. Navigation equations are derived for four classes of users: a relatively sophisticated user, such as a supersonic transport, desiring maximum accuracy; a user with more limited computational facilities than the SST, but who requires a reasonably high degree of accuracy; the simplest class of user, who will use charts and make hand calculations to compute position; and a user who is provided additional data to make his computations nearly trivial. Computer programs are included.

VOLUME 3, by N. Estersohn and A. Garabedian. December 1967 (N68-31279; TRW-08710-6012-R000, V-3). - The basic NAVSTAR system, its key elements, and major functions are described; and the antenna, receiver, preprocessor, computer, and display and control subsystems are treated in detail. BINOR code, pulse compression, and fixed-tones preprocessor designs were considered; and computer sizing analysis is studied, and surveys of an aerospace computer and an electronic calculator/desk-top computer are made. New technology is mentioned, including methods of reducing memory costs. Ranging modulation studies for position location using a navigational satellite system are detailed.

VOLUME 4, by D. D. Otten. December 1967 (N68-31280; TRW-08710-6012-R000, V-4). - Requirements are considered for the ground system to support an air traffic navigation system consisting of a two-orbit network with eight synchronous satellites in each orbit. A network of supporting ground stations is proposed, with the distribution of tracking sites designed for high accuracy. Location of the various stations, their functional descriptions, and some preliminary cost estimates are presented. Navigation signal generation, the L-band transmitter for the navigation signal system, and communications (voice) links are considered. Details relating to satellite design include structural requirements, mass properties, electrical integration and power, antenna subsystems, antenna design and attitude control, propulsion, and thermal control. System and subsystems reliability are discussed as are a survey of very stable oscillators, satellite oscillator reset, and command requirements and telemetry measurements.

VOLUME 5: APPENDUM, by A. Garabedian. October 1968 (N68-38306; TRW-08710-6012-R005). - Data links to provide full duplex communications between NAVSTAR system users and ground stations are considered in terms of air traffic control (ATC) capability for the satellites. Traffic control links and communications equipment required for ground stations, aircraft, and satellites are described; and estimated data requirements for surveillance and link power budgets are given. The satellite tracking data relay function and the impact on the satellite of adding the increased communication for traffic control are discussed. User hardware costs to implement the traffic control communications are estimated, assuming a production run of 200 units.

4. A SATELLITE SYSTEM TO SUPPORT AN ADVANCED AIR TRAFFIC CONTROL CONCEPT, by J. B. Woodford. January 1970 (AD-700 042).

This report describes a potential air traffic control system capable of meeting the demands of the United States through the 1990's. The report includes some gross cost analyses.

The Troposphere and Satellite Navigation

5. TROPOSPHERIC REFRACTION CORRECTIONS FOR AIRBORNE SYSTEMS, by P. M. Kalaghan and E. E. Altshuler. AFCRL-TR-0376, June 1973.

This report considers tropospheric range error calculations relative to low elevation angles. In addition, the author considers assumptions for tropospheric modeling.

6. CORRECTIONS FOR TROPOSPHERIC RANGE ERROR, by E. E. Altshuler. AFCRL-71-0419, July 1971.

This paper presents a simple empirical expression for tropospheric range error when satellite elevation angles are greater than 5°.

7. TROPOSPHERIC RANGE ERROR CORRECTIONS FOR THE NAVSTAR SYSTEM (with errata), by E. E. Altshuler and P. M. Kalaghan. AFCRL-TR-0198, April 1974.

The author develops a model for the tropospheric signal delay and subsequent range error associated with the NAVSTAR high altitude satellite navigation system. For computer adaptation, the necessary calculations in this model require only addition, subtraction, multiplication, and division, and the results compare with those obtained in reference 6 above.

8. PROCEEDINGS OF THE SECOND TROPOSPHERIC REFRACTION EFFECTS TECHNICAL REVIEW MEETING, prepared by the Mitre Corporation.

VOLUME 1, March 1964 (AD-435 973)

VOLUME 2, April 1964 (AD-441 576)

This report, actually in three volumes of which only two are referenced here, includes numerous papers on tropospheric effects, multipath, and instrumentation. Of particular interest is a paper by K. Norton entitled "Effects of Tropospheric Refraction in Earth-Space Links" found in volume 1. The paper by Norton is a survey of knowledge of tropospheric refraction phenomena.

9. PREDICTION TECHNIQUES FOR THE EFFECT OF THE IONOSPHERE ON PSEUDO-RANGING FROM SYNCHRONOUS ALTITUDE SATELLITES, by V. L. Pisacane, M. M. Feen, and M. Sturmanis. August 1972 (AD-749-486).

This paper analyzes ionospheric effects on the range information from synchronous orbit satellites. The authors discuss factors to be considered for precise ranging as it relates to position determination.

10. A TWO-QUARTIC REFRACTIVITY PROFILE FOR THE TROPOSPHERE FOR CORRECTING SATELLITE DATA, by H. S. Hopfield. September 1968 (AD-685 217).

A new model of the height profile of tropospheric refractivity is presented as the basis for an improved tropospheric correction for satellite doppler or range data.

Multipath

11. EFFECTS OF MULTIPATH ON RANGING ERROR FOR AN AIRPLANE-SATELLITE LINK, by P. A. Bello and C. J. Boardman. IEEE Transactions on Communications, vol. 21, no. 5, 564-576, May 1973.

This is an analysis on the effects of noise and surface scatter multipath in an airplane-satellite link.

12. SOME OBSERVATIONS OF SATELLITE/AIRCRAFT MULTIPATH PROPERTIES AT 1600 MHZ, by S. Karp. IEEE Transactions on Communications, vol. 22, no. 10, 1720-1722, October 1974.

Since 1600 MHZ is in the frequency range of the NAVSTAR system, this paper is of particular interest in a study of the multipath problems associated with NAVSTAR.

NAVSTAR GPS

13. TEST PLAN FOR NAVSTAR NAVIGATION SYSTEM, by TRW Systems Group, Redondo Beach, Calif. November 1968.

VOLUME 1 (N69-2851; TRW-08710-6023-R0-00). - The test plan described develops a series of tests for evaluating the NAVSTAR navigation system. The test sequence includes the following four types: (1) laboratory tests, using a precision oscillator, BINOR code generator, and low power L-band transmitter connected through an attenuator to a time division multiplex receiver and range acquisition unit; (2) field tests, using a receiving aircraft and/or helicopter to simulate a user and signal sources; (3) ERS (piggyback-launched satellite) test, using a low-orbiting satellite carrying the BINOR code signal portion of the navigation signal subsystem plus supporting subsystems; and (4) demonstration test using four of the IDCSP satellites for transponding range signals among a network of ground stations. Budgetary and planning type cost estimates plus schedules for the laboratory and field tests are also given.

VOLUME 2, (N69-28652; TRW-08710-6024-R0-00). - The satellite proposed for the NAVSTAR test program is one member of an existing family of Environmental Research Satellites (ERS). The test satellite is configured to provide a highly accurate check on range measurements at a ground station by carrying a MISTRAM "B" transponder in addition to the range equipment. The satellite weighs 68 pounds and carries as the experimental payload a stable oscillator, a BINOR code generator, an L-band transmitter and a MISTRAM B transponder for obtaining highly accurate range and range-rate data at the ground facility. A separate VHF transmitter is included which will transmit status performance data on the satellite systems. The satellite is also command controlled by a VHF command link. A simpler test satellite design which does not include the MISTRAM system is also described. The satellite in this case weighs about 32 pounds and carries only the L-band BINOR code system as the experimental payload. The orbit for this configuration would be the same as for the MISTRAM configuration.

The following six documents comprise the specifications for the NAVSTAR Global Positioning System, and are available from Space And Missile Systems Organization, El Segundo, California.

14. SYSTEM SPECIFICATIONS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM, PHASE I, APPENDICES I AND II, SCN 1 and 2, SS-GPS-101B, Code Identification 07868. SAMSO/YEN.

15. SYSTEM SEGMENT SPECIFICATIONS FOR THE CONTROL SYSTEM SEGMENT OF THE NAVSTAR GLOBAL POSITIONING SYSTEM, PHASE I, SS-CS-101A, Code Identification 07868. SAMSO/YEN.

16. SPECIFICATIONS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM INVERTED RANGE, STE-IR-101A, Code Identification 07868. SAMSO/YEN.

17. USER SYSTEM SEGMENT SPECIFICATIONS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM, PHASE I, SS-US-101A, Code Identification 07868. SAMSO/YEN

18. SPECIFICATIONS FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM TEST POD, STE-TP-101A, Code Identification 07868. SAMSO/YEN.

19. PROGRAM TEST PLAN FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM, PHASE I, ANNEX I, INTEGRATED LOGISTICS SUPPORT PLAN, YEN-74-102A, Code Identification 07868. SAMSO/YEN.

20. NAVSTAR GLOBAL POSITIONING SYSTEM PROGRAM MANAGEMENT PLAN. SAMSO/YE. July 1974.

This document establishes Joint Service Program executive policies and implementing procedures for the management and acquisition of the NAVSTAR Global Positioning System throughout its life cycle.

Miscellaneous Reports Associated With Satellite Navigation

21. UNMANNED SPACECRAFT FOR RESEARCH, by C. D. Graves. 1972 (N73-13830).

The applications of unmanned spacecraft for research purposes are discussed. Specific applications of the communication and navigation satellites and the earth observation satellites are described. Diagrams of communications on a world-wide basis using synchronous satellites are developed. Photographs of earth resources and geology obtained from space vehicles are included.

22. NAVIGATION WITH HIGH-ALTITUDE SATELLITES: A STUDY OF ERRORS IN POSITION DETERMINATION, by D. L. Snyder. February 1967 (AD-648 828).

Position determination by use of a high-altitude satellite navigation system is investigated. The basis for the error analysis is a system modelled as a problem of nonlinear estimation.

23. NAVIGATION WITH HIGH-ALTITUDE SATELLITES: A STUDY OF RANGING ERRORS, by T. J. Goblick, Jr. August 1966 (AD-643 851).

This paper considers the factors affecting user-to-satellite ranging. The author also includes a discussion of multipath effects as they relate to range determination.

24. ANALYSIS OF SATELLITE NAVIGATION SYSTEM STUDIES (Unclassified title for a classified document), (AD-516-565L).

25. ACCURACY OF DEFLECTION OF THE VERTICAL DERIVED FROM SATELLITE ALTIMETRY, by C. J. Cohen and B. Zondek. October 1971 (AD-889 056L).

This paper is referenced here because of its discussion of a geoid model and the interaction of the model with signal structure.

Satellite Navigation Systems

26. NAVIGATION SATELLITE CONSTELLATION STUDY, by F. M. Holmes. November 1967 (AD-831 108).

This report is an analysis of satellite configurations and associated accuracies assuming the system to be the range difference type. The primary uses of this report are to provide a method for examining satellite visibility, provide a method for the determination of user errors, provide estimates of accuracy with which satellites may be tracked in various orbits, and provide tables of theoretical accuracy.

27. CONSTELLATION STUDY FOR SATELLITE NAVIGATION WITH PASSIVE RANGING, by D. A. Conrad. May 1968 (AD-834 284).

This report is useful in gaining an insight into the concepts of passive ranging from a satellite system. Included is a good discussion of oscillators and the problems arising from instabilities.

28. TIMATION NAVIGATION SATELLITE SYSTEM CONSTELLATION STUDY, by J. A. Buisson and T. B. McCaskill. June 1972 (AD-902 178L).

This report is a study conducted by the Naval Research Laboratory of the TIMATION technique of passive ranging. It deals primarily with the feasibility of constellation structuring.

29. ANALYSIS OF NAVIGATION ERROR SOURCES FOR THE TIMATION DNSS, by E. R. Swift. November 1973 (AD-774 912).

This report is an error analysis for the TIMATION satellite navigation system. The tropospheric model used is based on work by Hopfield found in "Tropospheric Effect on Electromagnetically Measured Range: Prediction from

Surface Weather Data", Radio Science, volume 6, number 3, 1971.

30. TACTICAL SATELLITE NAVIGATION SYSTEM STUDY, by K. D. McDonald, K. M. Joyce, and R. J. Yoo. November 1968 (AD-849 347).

This report involves the analysis of navigation satellite techniques for use with Army tactical aircraft. This presentation covers the evaluation of such technical disciplines as the sensors and their measurement errors, timing systems and their accuracies, and the impact of the frequency and modulation choices on propagation losses and system efficiencies.

31. A SELECTED BIBLIOGRAPHY ON THE USES OF NAVIGATION SATELLITES, By C. R. Burt. October 1967 (AD-821 230).

This bibliography on the uses of navigation satellites covers the open published and report literature from 1960 to 1967. It contains 86 listings of which several were researched for background material in preparation of this thesis.

V. Summary

Development of the mathematical relationships necessary for finding the intersection of three spheres, and for rotating and translating the original axis system to this intersection are outlined in Chapter II. This intersection is then analyzed assuming the radii of the spheres to be independent, zero mean, gaussian random variables. These mathematical relationships and random variable concepts then form the basis for a computer program designed to solve for position variances resulting from tropospheric effects on passive ranging and the subsequent position determination associated with the NAVSTAR Global Positioning System. The range errors and linearly related variances calculated with this program agree with values estimated by Altshuler. A comprehensive source listing of material covering all aspects of satellite navigation has been compiled. The references in this listing are intended to provide the reader with both background information and current thought in such areas as multipath propagation, air traffic control employing satellites, error analysis, and research previously undertaken by the Air Force, Navy, and Army. The versatility of the computer program has been discussed with examples of output variations converted to graphs and presented in Figs. 7 and 8. A computer card deck is maintained at the Air Force Institute of Technology, Department of Electrical Engineering (AFIT/ENE), Wright Patterson Air Force Base, Ohio 45433.

Bibliography

1. Altshuler, E. E. Corrections for Tropospheric Range Error. AFCRL-71-0419. Bedford, Massachusetts: Air Force Cambridge Research Laboratory, 1971.

2. Altshuler, E. E. and P. M. Kalaghan. Tropospheric Range Error Corrections for the NAVSTAR System. AFCRL-TR-74-0198. Bedford, Massachusetts: Air Force Cambridge Research Laboratory, 1974.

3. Bajpai, A. C., et al. Engineering Mathematics. New York: John Wiley & Sons, 1974.

4. Bate, Roger R., et al. Fundamentals of Astrodynamics. New York: Dover Publications, Inc., 1971.

5. Buisson, J. A. and T. B. McCaskill. Timation Navigation Satellite System Constellation Study. NRL-7389. Washington D. C.: Naval Research Laboratory. June 1972. AD-902 178.

6. Davenport, W. B., Jr. Probability and Random Processes. St. Louis: McGraw-Hill Book Co., 1970.

7. Hutcheson, J. H. Possible Utility of the TRANSIT System for Air Force Navigation. RM-5031-PR. June 1966. (Confidential Report) AD-373 935.

8. Montgomery, B. O., et al. Flight Test of the 621B NAVSAT System. AFSWC -TR-73-2. Kirtland Air Force Base, New Mexico: Air Force Special Weapons Center, January 1973. AD-907 451L.

9. Simpson, Richard S. and Ronald C. Houts. Fundamentals of Analog and Digital Communications Systems. Boston: Allyn and Bacon, Inc., 1971.

10. Space and Missile Systems Organization. NAVSTAR Global Positioning System Program Management Plan. El Segundo: SAMSO/YEN, July 1974.

11. Space and Missile Systems Organization. System Specifications for the NAVSTAR Global Positioning System. SS-GPS-101B, Code Identification 07868. El Segundo: SAMSO/YEN, August 1974.

12. Thomas, G. B., Jr. Calculus and Analytical Geometry (Third Edition). Reading, Massachusetts: Addison-Wesley Publishing Company, Inc., 1962.

Appendix A

Output Variations

The first format is a typical user position solution and associated variances given the position of three satellites and respective user-to-satellite range information.

The second format shows the tabulated output obtained from the VARPROF subroutine.

The third format lists the position variances for any selected combination of three satellites.

```
USER POSITION

ALTITUDE(FT) =          .4252172E+05     THETA(DEG) =  111.16     PHI(DEG) =   12.66

POSITION VARIANCES(FTXFT) ARE:

VN =       .003     VE =       .003     VH =       .004
```

ALTITUDE = 100.0 FEET

SATEL1(DEG)	THET1(DEG)	SATEL2(DEG)	THET2(DEG)	SATEL3(DEG)	THET3(DEG)	VN(FTXFT)	VE(FTXFT)	VM(FTXFT)
10.00	90.00	10.00	90.00	10.00	90.00	.000	7.737	.241
10.00	90.00	10.00	90.00	10.00	180.00	2.579	5.158	.241
10.00	90.00	10.00	90.00	10.00	270.00	.000	7.737	.241
10.00	90.00	10.00	90.00	10.00	360.00	2.579	5.158	.241
10.00	90.00	10.00	90.00	40.00	90.00	.000	5.279	.245
10.00	90.00	10.00	90.00	40.00	180.00	.121	5.159	.245
10.00	90.00	10.00	90.00	40.00	270.00	.000	5.279	.245
10.00	90.00	10.00	90.00	40.00	360.00	.121	5.159	.245
10.00	90.00	10.00	90.00	70.00	90.00	.000	5.170	.246
10.00	90.00	10.00	90.00	70.00	180.00	.011	5.158	.246
10.00	90.00	10.00	90.00	70.00	270.00	.000	5.170	.246
10.00	90.00	10.00	90.00	70.00	360.00	.011	5.158	.245
10.00	90.00	10.00	180.00	10.00	90.00	2.579	5.159	.241
10.00	90.00	10.00	180.00	10.00	180.00	5.159	2.579	.241
10.00	90.00	10.00	180.00	10.00	270.00	2.579	5.158	.241
10.00	90.00	10.00	180.00	10.00	360.00	5.159	2.579	.241
10.00	90.00	10.00	180.00	40.00	90.00	2.579	2.700	.245
10.00	90.00	10.00	180.00	40.00	180.00	2.700	2.579	.245
10.00	90.00	10.00	180.00	40.00	270.00	2.579	2.700	.245
10.00	90.00	10.00	180.00	40.00	360.00	2.700	2.579	.245
10.00	90.00	10.00	180.00	70.00	90.00	2.579	2.590	.246
10.00	90.00	10.00	180.00	70.00	180.00	2.590	2.579	.246
10.00	90.00	10.00	180.00	70.00	270.00	2.579	2.590	.245
10.00	90.00	10.00	180.00	70.00	360.00	2.590	2.579	.246
10.00	90.00	10.00	270.00	10.00	90.00	.000	7.737	.241
10.00	90.00	10.00	270.00	10.00	180.00	2.579	5.159	.241
10.00	90.00	10.00	270.00	10.00	270.00	.000	7.737	.241
10.00	90.00	10.00	270.00	10.00	360.00	2.579	5.158	.241
10.00	90.00	10.00	270.00	40.00	90.00	.000	5.279	.245
10.00	90.00	10.00	270.00	40.00	180.00	.121	5.159	.245
10.00	90.00	10.00	270.00	40.00	270.00	.000	5.279	.245
10.00	90.00	10.00	270.00	40.00	360.00	.121	5.159	.245
10.00	90.00	10.00	270.00	70.00	90.00	.000	5.170	.245
10.00	90.00	10.00	270.00	70.00	180.00	.011	5.153	.245
10.00	90.00	10.00	270.00	70.00	270.00	.000	5.170	.246
10.00	90.00	10.00	270.00	70.00	360.00	.011	5.159	.246
10.00	90.00	10.00	360.00	10.00	90.00	2.579	5.158	.241
10.00	90.00	10.00	360.00	10.00	180.00	5.159	2.579	.241
10.00	90.00	10.00	360.00	10.00	270.00	2.579	5.159	.241
10.00	90.00	10.00	360.00	10.00	360.00	5.158	2.579	.241
10.00	90.00	10.00	360.00	40.00	90.00	2.579	2.700	.245
10.00	90.00	10.00	360.00	40.00	180.00	2.700	2.579	.245
10.00	90.00	10.00	360.00	40.00	270.00	2.579	2.700	.245
10.00	90.00	10.00	360.00	40.00	360.00	2.700	2.579	.245
10.00	90.00	10.00	360.00	70.00	90.00	2.579	2.590	.245
10.00	90.00	10.00	360.00	70.00	180.00	2.590	2.579	.246
10.00	90.00	10.00	360.00	70.00	270.00	2.579	2.590	.246
10.00	90.00	10.00	360.00	70.00	360.00	2.590	2.579	.246
10.00	90.00	40.00	90.00	10.00	90.00	.000	5.279	.245
10.00	90.00	40.00	90.00	10.00	180.00	2.579	2.700	.245
10.00	90.00	40.00	90.00	10.00	270.00	.000	5.279	.245
10.00	90.00	40.00	90.00	10.00	360.00	2.579	2.700	.245
10.00	90.00	40.00	90.00	40.00	90.00	.000	2.920	.250
10.00	90.00	40.00	90.00	40.00	180.00	.121	2.700	.250
10.00	90.00	40.00	90.00	40.00	270.00	.000	2.920	.250
10.00	90.00	40.00	90.00	40.00	360.00	.121	2.700	.250
10.00	90.00	40.00	90.00	70.00	90.00	.000	2.711	.250
10.00	90.00	40.00	90.00	70.00	180.00	.011	2.700	.250
10.00	90.00	40.00	90.00	70.00	270.00	.000	2.711	.250
10.00	90.00	40.00	90.00	70.00	360.00	.011	2.700	.250

```
SATEL(1) =  70.0     THET(1) =  45.00
(DEGREES)            (DEGREES)
SATEL(2) =  80.00    THET(2) = 135.00
(DEGREES)            (DEGREES)
SATEL(3) =  90.00    THET(3) = 315.00
(DEGREES)            (DEGREES)

VN(FTXFT) =    .007     VE(FTXFT) =    .007     VH(FTXFT) =    .244
```

Appendix B

Computer Program

This appendix contains a computer generated listing of the NAVSTAR computer program and and the eight subroutines required for tropospheric error analysis.

```
PROGRAM NAVSTAR    74/74    OPT=1                            FTN 4.2+P380       01/17/75  08.42.59.

          PROGRAM NAVSTAR(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)                000100
          COMMON X,Y,Z,R,THETA,XN,YN,ZN,AX,AY,AZ,N,SATEL                        000110
          REAL N                                                                000120
          DIMENSION X(6),Y(6),Z(6),RHO(5),THETA(5),PHI(5),R(3),                 000130
         1XN(3),YN(3),ZN(3),AX(3),AY(3),AZ(3),SATEL(3),DR(3),RC(3)             000140
          PI=4.0*ATAN(1.0)                                                      000150
    5     DO 20 I=1,3                                                           000160
*****************************************************************               000170
*         RHO,THETA,PHI - POLAR COORDINATES OF THE SATELLITE          *         000180
*                         POSITIONS IN THE GEOCENTRIC SYSTEM          *         000190
*         R - UNCORRECTED SATELLITE-TO-USER RANGE INFORMARION         *         000200
*         ALT - USERS'S ALTITUDE ABOVE SEA-LEVEL(FEET)                *         000210
*         N - SURFACE INDEX OF REFRACTION                             *         000220
*                                                                     *         000230
*         NOTE: IF THE LAST TWO PARAMETERS ARE UNKNOWN, THEY          *         000240
*         MUST BE SET TO ZERO.                                        *         000250
*****************************************************************               000260
          READ 10,RHO(I),THETA(I),PHI(I),R(I)                                   000270
          IF(EOF(5).NE.0)GO TO 70                                               000280
   10     FORMAT(4F15.0)                                                        000290
   20     CONTINUE                                                              000300
          READ 30,ALT,N,SATEL(1),SATEL(2),SATEL(3)                              000310
   30     FORMAT(F15.0,F5.0,3F15.0)                                             000320
          CN=0.0                                                                000330
          CALL PTOR(RHO,THETA,PHI,X,Y,Z)                                        000340
          IF(N.NE.0.0)GO TO 40                                                  000350
          N=324.8                                                               000360
          CN=1                                                                  000370
   40     IF(ALT.NE.0.0)GO TO 50                                                000380
          CALL ALTEST(RHO,PHI,ALT)                                              000390
**********************************************************************          000400
*         ALTITUDE AND SATELLITE ELEVATION ANGLE ARE NORMALLY          *        000410
*         INPUT PARAMETERS.  THE ALTEST SUBROUTINE IS ONLY USED        *        000420
*         TO GENERATE THESE PARAMETERS FOR PROBLEM SIMULATION.         *        000430
**********************************************************************          000440
   50     CALL DELTAR(SATEL,ALT,N,DR)                                           000450
          DO 55 I=1,3                                                           000460
          RC(I)=R(I)-DR(I)                                                      000470
   55     CONTINUE                                                              000480
          CALL PSN(X,Y,Z,RC,RHO,THETA,PHI,ALT)                                  000490
          CALL [illegible](X,Y,Z,RHO,THETA,PHI,XN,YN,ZN,AX,AY,AZ,SATEL)         000500
          CALL VAR(AX,AY,AZ,DR,VN,VE,VH,CN)                                     000510
          THETA(5)=THETA(5)*180.0/PI                                            000520
          PHI(5)=PHI(5)*180.0/PI                                                000530
          WRITE 65,ALT,THETA(5),PHI(5)                                          000540
   65     FORMAT(*1*,/,5X,*USER POSITION*,//,5X,*ALTITUDE(FT) = *,E20.7,5X,     000550
         1*THETA(DEG) = *,F7.2,5X,*PHI(DEG) = *,F7.2,/)                         000560
          PRINT 60,VN,VE,VH                                                     000570
   60     FORMAT(/,5X,*POSITION VARIANCES(FTXFT) ARE:*,//,5X,*VN = *,F9.3,      000580
         15X,*VE = *,F9.3,5X,*VH = *,F9.3)                                      000590
```

```
PROGRAM NAVSTAR    74/74    OPT=1                          FTN 4.2+P380        01/17/75  08.42.59.
      ************************************************************          000600
      *     N AND CN ARE SET HERE FOR A SAMPLE RUN. THESE VALUES     *          000610
      *     WOULD NORMALLY BE TAKEN FROM INPUT DATA OR ASSUMED       *          000620
      *     WITH THE FLAG, CN, SET TO                                *          000630
      ************************************************************          000640
            GO TO 5                                                         000650
    70      N=724.0                                                         000660
            CN=3.0                                                          000670
            ALT=100.0                                                       000680
            CALL VARPROF(ALT,N,CN)                                          000690
            STOP                                                            000700
            END                                                             000710
```

```
SUBROUTINE ORBSYS      74/74    OPT=1                              FTN 4.2+P380        01/17/75  08.43.02.

            SUBROUTINE ORBSYS(X,Y,Z,RHO,THETA,PHI,XN,YN,ZN,AX,AY,AZ,                    000720
           1SATEL)                                                                      000730
            REAL LN                                                                     000740
            DIMENSION X(6),Y(6),Z(6),RHO(5),THETA(5),PHI(5),XN(3),                      000750
           1YN(3),ZN(3),AX(3),AY(3),AZ(3),SATEL(3),LN(3)                                000760
      ******************************************************************                000770
      *     THIS SUBROUTINE TRANSPOSES SATELLITE POSITION FROM                 *        000780
      *     A GEOCENTRIC CARTESIAN COORDINATE SYSTEM TO AN                     *        000790
      *     ORTHOGONAL COORDINATE SYSTEM CENTERED ON THE USER.                 *        000800
      *     IT THEN CALCULATES THE DIRECTION COSINE ANGLES                     *        000810
      *     FOR EACH SATELLITE VECTOR.                                         *        000820
      ******************************************************************                000830
            DO 10 I=1,3                                                                 000840
            XN(I)=-Z(I)*SIN(PHI(5))-(X(I)*COS(THETA(5))+Y(I)*SIN(                       000850
           1THETA(5)))*COS(PHI(5))-RHO(5)                                               000860
            YN(I)=Y(I)*COS(THETA(5))-X(I)*SIN(THETA(5))                                 000870
            ZN(I)=+Z(I)*COS(PHI(5))-(X(I)*COS(THETA(5))+Y(I)*SIN(                       000880
      **************************************************************                    000890
      *    XN,YN,ZN - SATELLITE COORDINATES IN ORTHOGONAL SYSTEM       *                000900
      *               CENTERED ON THE USER.                            *                000910
      *    AX,AY,AZ - DIRECTION COSINE ANGLES OF THE RANGE VECTOR      *                000920
      *               IN ORTHOGONAL SYSTEM CENTERED ON THE USER        *                000930
      **************************************************************                    000940
           1THETA(5)))*SIN(PHI(5))                                                      000950
            LN(I)=SQRT(XN(I)**2+YN(I)**2+ZN(I)**2)                                      000960
            AX(I)=1.0/ATAN(XN(I)/SQRT(ZN(I)**2+YN(I)**2))                               000970
            AY(I)=ACOS(YN(I)/LN(I))                                                     000980
            AZ(I)=ACOS(ZN(I)/LN(I))                                                     000990
            SATEL(I)=ATAN(XN(I)/SQRT(ZN(I)**2+YN(I)**2))                                001000
   10       CONTINUE                                                                    001010
            RETURN                                                                      001020
            END                                                                         001030
```

```
SUBROUTINE DELTAR      74/74    OPT=1                         FTN 4.2+P380       01/17/75  08.43.04.

           SUBROUTINE DELTAR(SATELI,ALT,N,DR)                                    001040
      ***************************************************************            001050
      *    THIS SUBROUTINE CALCULATES THE RANGE ERROR, DR. SATEL-    *           001060
      *    LITE ELEVATION ANGLE, SATELI, IS WITH RESPECT TO THE      *           001070
      *    USER.                                                     *           001080
      ***************************************************************            001090
           REAL N                                                                001100
           DIMENSION SATEL(3),DR(3),SATELI(3)                                    001110
           ALTI=ALT/1000.0                                                       001120
           DO 10 I=1,3                                                           001130
           SATEL(I)=SATELI(I)*180.0/(4.0*ATAN(1.0))                              001140
           DR(I)=((4.79+0.33972*N)/SIN(SATELI(I))-(0.00586*(N-360)**2+           001150
          1294)/SATEL(I)**2.30)/EXP((6.07E-5*N+.0213)*ALTI+(8.877/               001160
          1N-1.58E-4)*ALTI**2)                                                   001170
      10   CONTINUE                                                              001180
           RETURN                                                                001190
           END                                                                   001200
```

```
SUBROUTINE VAR          74/74    OPT=1                          FTN 4.2+P380        01/17/75  08.43.19.

             SUBROUTINE VAR(AX,AY,AZ,DR,VN,VE,VH,CN)                                  001210
        *************************************************************                 001220
        *    THIS SUBROUTINE CALCULATES THE POSITION VARI-                  *         001230
        *    ABLES OF THE SYSTEM USER IN ALTITUDE, EAST-                    *         001240
        *    WEST DIRECTION, AND NORTH-SOUTH DIRECTION.                     *         001250
        *************************************************************                 001260
             DIMENSION V(3),AX(3),AY(3),AZ(3),DR(3)                                   001270
             IF(CN.NE.0.0)GO TO 20                                                    001280
             DO 10 I=1,3                                                              001290
             V(I)=.337*DR(I)                                                          001300
        10   CONTINUE                                                                 001310
             GO TO 40                                                                 001320
        20   DO 30 I=1,3                                                              001330
             V(I)=.001*DR(I)                                                          001340
        30   CONTINUE                                                                 001350
        40   VH=(V(1)*COS(AX(1)))**2+(V(2)*COS(AX(2)))**2                             001360
            1+(V(3)*COS(AX(3)))**2                                                    001370
             VN=(V(1)*COS(AZ(1)))**2+(V(2)*COS(AZ(2)))**2+(V(3)                       001380
            1*COS(AZ(3)))**2                                                          001390
             VE=(V(1)*COS(AY(1)))**2+(V(2)*COS(AY(2)))**2+(V(3)                       001400
            1*COS(AY(3)))**2                                                          001410
             RETURN                                                                   001420
             END                                                                      001430
```

```
SUBROUTINE ALTEST      74/74    OPT=1                           FTN 4.2+P380       01/17/75  08.43.21.

                   SUBROUTINE ALTEST(RHO,PHI,ALT)                                          001440
                   REAL N                                                                  001450
                   COMMON X,Y,Z,R,THETA,XN,YN,ZN,AX,AY,AZ,N,SATEL                          001460
                   DIMENSION X(6),Y(6),Z(6),RHO(5),THETA(5),PHI(5),XN(3),                  001470
                  1YN(3),ZN(3),AX(3),AY(3),AZ(3),SATEL(3),DR(3),R(3),D(3),E(3)             001480
                   PI=4.0*ATAN(1.0)                                                        001490
                   PIOVER2=2.0*ATAN(1.0)                                                   001500
                   ER=2.092647049E+07                                                      001510
                   DO 10 I=1,3                                                             001520
                   D(I)=R(I)                                                               001530
                   E(I)=0.0                                                                001540
              10   CONTINUE                                                                001550
                   DELTASL=0.007043932E+07                                                 001560
              20   CALL PSN(X,Y,Z,D,RHO,THETA,PHI,ALT)                                     001570
                   ALT=RHO(5)-(-DELTASL*ABS(PIOVER2-PHI(5))/PI*2+ER)                       001580
                   CALL DRCSNS(X,Y,Z,RHO,THETA,PHI,XN,YN,ZN,AX,AY,AZ,SATEL)                001590
                   CALL DELTAR(SATEL,ALT,N,DR)                                             001600
                   DO 30 I=1,3                                                             001610
                   D(I)=R(I)-DR(I)                                                         001620
              30   CONTINUE                                                                001630
                   IF(ABS(D(1)-E(1)).LE..01)GO TO 40                                       001640
                   GO TO 60                                                                001650
              40   IF(ABS(D(2)-E(2)).LE..01)GO TO 50                                       001660
                   GO TO 60                                                                001670
              50   IF(ABS(D(3)-E(3)).LE..01)GO TO 80                                       001680
                   GO TO 60                                                                001690
              60   DO 70 I=1,3                                                             001700
                   E(I)=D(I)                                                               001710
              70   CONTINUE                                                                001720
                   GO TO 20                                                                001730
              80   RETURN                                                                  001740
                   END                                                                     001750
```

```
SUBROUTINE PTOR       74/74    OPT=1                   FTN 4.2+P380       01/17/75  03.43.28.

            SUBROUTINE PTOR(RHO,THETA,PHI,X,Y,Z)                                  001760
            DIMENSION RHO(5),THETA(5),PHI(5),X(6),Y(6),Z(6)                       001770
            DO 10 I=1,3                                                           001780
            X(I)=RHO(I)*SIN(PHI(I))*COS(THETA(I))                                 001790
            Y(I)=RHO(I)*SIN(PHI(I))*SIN(THETA(I))                                 001800
            Z(I)=RHO(I)*COS(PHI(I))                                               001810
   10       CONTINUE                                                              001820
            RETURN                                                                001830
            END                                                                   001840
```

```
SUBROUTINE PSN        74/74    OPT=1                      FTN 4.2+P380        01/17/75  08.43.29.

                SUBROUTINE PSN(X,Y,Z,R,RHO,THETA,PHI,ALT)                                     001850
                REAL J,K,L,M,N                                                                001860
                DIMENSION X(6),Y(5),Z(6),RHO(5),THETA(5),PHI(5),T(2),R(3)                     001870
                RE=2.092647049E+07                                                            001880
                PIOVER2=2.0*ATAN(1.0)                                                         001890
                DELTASL=.3070459332E+07                                                       001900
                A=R(1)**2-(X(1)**2+Y(1)**2+Z(1)**2)                                           001910
                B=R(2)**2-(X(2)**2+Y(2)**2+Z(2)**2)                                           001920
                C=R(3)**2-(X(3)**2+Y(3)**2+Z(3)**2)                                           001930
                D=-2*X(1)                                                                     001940
                E=-2*Y(1)                                                                     001950
                F=-2*Z(1)                                                                     001960
                G=-2*X(2)                                                                     001970
                H=-2*Y(2)                                                                     001980
                J=-2*Z(2)                                                                     001990
                K=-2*X(3)                                                                     002000
                L=-2*Y(3)                                                                     002010
                M=-2*Z(3)                                                                     002020
            ********************************************************************             002030
            *   THREE SPHERES IN A CARTESIAN COORDINATE SYSTEM ARE              *             002040
            *   REPRESENTED BY THE THREE EQUATIONS:                             *             002050
            *                                                                   *             002060
            *   1. X**2 + DX + Y**2 + EY + Z**2 + FZ = A                        *             002070
            *   2. X**2 + GX + Y**2 + HY + Z**2 + JZ = B                        *             002080
            *   3. X**2 + KX + Y**2 + LY + Z**2 + MZ = C                        *             002090
            *                                                                   *             002100
            *   THE INTERSECTION OF TWO OVRLAPPING SPHERES IS A                 *             002110
            *   CIRCLE IN THREE-DIMENSIONS.  THE PLANES CONTAINING              *             002120
            *   TWO OF THESE INTERSECTIONS, SPHERES 1 AND 2, AND                *             002130
            *   SPHERES 1 AND 3, ARE                                            *             002140
            *                                                                   *             002150
            *   P1-2. (D-G)X + (E-H)Y + (F-J)Z = A-B                            *             002160
            *   P1-3. (D-K)X + (E-L)Y + (F-M)Z = A-C                            *             002170
            *                                                                   *             002180
            *   THESE TWO PLANES INTERSECT IN A LINE WHICH CAN                  *             002190
            *   BE REPRESENTED PARAMETRICALLY                                   *             002200
            *                                                                   *             002210
            *   X = NT + X(4)     Y = OT + Y(4)     Z = PT + Z(4)               *             002220
            *                                                                   *             002230
            *   WHERE X(4),Y(4), AND Z(4) REPRESENT ANY POINT ON                *             002240
            *   THE LINE.                                                       *             002250
            ********************************************************************             002260
                N=(E-H)*(F-M)-(E-L)*(F-J)                                                     002270
                O=(D-G)*(F-M)-(D-K)*(F-J)                                                     002280
                P=(D-G)*(E-L)-(D-K)*(E-H)                                                     002290
            ********************************************************************             002300
            *   N, O, AND P REPRESENT THE COEFFICIENTS OF THE                   *             002310
            *   VECTOR RESULTING FROM THE CROSS PRODUCT OF NORMALS              *             002320
            *   TO THE TWO PLANES                                               *             002330
            ********************************************************************             002340
```

```
SUBROUTINE PSN        74/74    OPT=1                          FTN 4.2+P380        01/17/75  08.43.29.

             AA=(E-H)*(F-M)-(E-L)*(F-J)                                                  002350
             AB=(D-G)*(F-M)-(D-K)*(F-J)                                                  002360
             AC=(D-G)*(F-L)-(D-K)*(F-H)                                                  002370
             IF(AA.EQ.0.0)GO TO 2                                                        002380
             X(4)=1.0                                                                    002390
             Y(4)=((A-B-E+G)*(F-M)-(A-C-D+K)*(F-J))/((E-H)*(F-M)-(E-L)*(F-J))            002400
             Z(4)=((A-B-(E-H)*Y(4)-(D-G))/(F-J)                                          002410
             GO TO 6                                                                     002420
        2    IF(AB.EQ.0.0)GO TO 4                                                        002430
             Y(4)=1.0                                                                    002440
             X(4)=((A-B-E+H)*(F-M)-(A-C-E+L)*(F-J))/((D-G)*(F-M)-(D-K)*(F-J))            002450
             Z(4)=(A-B-E+H-(D-G)*X(4))/(F-J)                                             002460
             GO TO 6                                                                     002470
        4    Z(4)=1.0                                                                    002480
             X(4)=((A-B-F+J)*(E-L)-(A-C-F+M)*(E-H))/((D-G)*(E-L)-(D-K)*(E-H))            002490
             Y(4)=(A-B-F+J-(D-G)*X(4))/(E-H)                                             002510
        6    Q=N**2+O**2+P**2                                                            002510
             S=X(4)**2+Y(4)**2+Z(4)**2-A+D*X(4)+E*Y(4)+F*Z(4)                            002520
             U=2*X(4)*N+D*N+2*O*Y(4)+E*O+2*Z(4)*P+F*P                                    002530
      ***************************************************************                   002540
      *      SUBSTITUTION OF THE PARAMETRIC EQUATIONS INTO                 *             002550
      *      ANY OF THE SPHERICAL EQUATIONS YEILDS A QUAD-                 *             002560
      *      RATIC EQUATION IN "T".                                        *             002570
      ***************************************************************                   002580
             T(1)=(-U+SQRT(U**2-4.0*Q*S))/(2.0*Q)                                        002590
             T(2)=(-U-SQRT(U**2-4.0*Q*S))/(2.0*Q)                                        002600
      ***************************************************************                   002610
      *      THE SOLUTION IS TWO POINTS IN THREE-SPACE                     *             002620
      ***************************************************************                   002630
             X(5)=N*T(1)+X(4)                                                            002640
             X(6)=N*T(2)+X(4)                                                            002650
             Y(5)=O*T(1)+Y(4)                                                            002660
             Y(6)=O*T(2)+Y(4)                                                            002670
             Z(5)=P*T(1)+Z(4)                                                            002680
             Z(6)=P*T(2)+Z(4)                                                            002690
             RHO(5)=SQRT(X(5)**2+Y(5)**2+Z(5)**2)                                        002700
             RHO(6)=SQRT(X(6)**2+Y(6)**2+Z(6)**2)                                        002710
             PHI(5)=ACOS(Z(5)/RHO(5))                                                    002720
             PHI(6)=ACOS(Z(6)/RHO(6))                                                    002730
             THETA(5)=ACOS(X(5)/(RHO(5)*SIN(PHI(5))))                                    002740
             THETA(6)=ACOS(X(6)/(RHO(6)*SIN(PHI(6))))                                    002750
             ALT1=RHO(5)-(-DELTASL*ABS(PIOVER2-PHI(5))/PIOVER2+ER)                       002760
             ALT2=RHO(6)-(-DELTASL*ABS(PIOVER2-PHI(6))/PIOVER2+ER)                       002770
             IF(ABS(ALT-ALT1).GT.ABS(ALT-ALT2))                                          002780
            1GO TO 10                                                                    002790
             GO TO 20                                                                    002800
       10    X(5)=X(6)                                                                   002810
             Y(5)=Y(6)                                                                   002820
             Z(5)=Z(6)                                                                   002830
       20    RHO(5)=SQRT(X(5)**2+Y(5)**2+Z(5)**2)                                        002840
             PHI(5)=ACOS(Z(5)/RHO(5))                                                    002850
             THETA(5)=ACOS(X(5)/(RHO(5)*SIN(PHI(5))))                                    002860
             RETURN                                                                      002870
             END                                                                         002880
```

```
SUBROUTINE VARPROF    74/74    OPT=1                          FTN 4.2+P390       01/17/75  08.43.46.

            SUBROUTINE VARPROF(ALT,N,CN)                                          002890
      *******************************************************************         002900
      *     THE VARPROF SUBROUTINE IS USED TO PRODUCE A POSITION        *         002910
      *     VARIANCE PROFILE AS A FUNCTION OF USER ALTITUDE,            *         002920
      *     SATELLITE ELEVATION ANGLES, AND ROTATION ANGLE OF           *         002930
      *     THE PLANE DEFINED BY THE VECTOR FROM THE EARTH              *         002940
      *     TO THE USER, AND THE SATELLITE.                             *         002950
      *                                                                 *         002960
      *         VN = NORTH-SOUTH VARIANCE(FTXFT)                        *         002970
      *         VL = EAST-WEST VARIANCE(FTXFT)                          *         002980
      *         VH = ALTITUDE VARIANCE(FTXFT)                           *         002990
      *                                                                 *         003000
      *     SATELLITE ELEVATION ANGLES MAY BE INCREMENTED FROM          *         003010
      *     5 DEGREES TO 90 DEGREES AND ROTATION ANGLES MAY BE          *         003020
      *     INCREMENTED FROM 1 DEGREE TO 360 DEGREES. ALTITUDE,         *         003030
      *     SURFACE INDEX OF REFRACTION, AND THE REFRACTION             *         003040
      *     INDEX FLAG, CN, MUST BE SPECIFIED TO CALL THE SUB-          *         003050
      *     ROUTINE.                                                    *         003060
      *******************************************************************         003070
            REAL N                                                                003080
            INTEGER O,P                                                           003090
            DIMENSION AX(3),AY(3),AZ(3),ED(3),RD(3),ER(3),RR(3),DR(3)             003100
            PI=4.0*ATAN(1.0)                                                      003110
            PRINT 5                                                               003120
      5     FORMAT(*5*)                                                           003130
            PRINT 10,ALT                                                          003140
      10    FORMAT(*1*,51X,*ALTITUDE =*,F7.1,1X,*FEET*)                           003150
            PRINT 20                                                              003160
      20    FORMAT(//,3X,*SATEL1(DEG)*,3X,*THET1(DEG)*,3X,*SATEL2(DEG)*,          003170
           13X,*THET2(DEG)*,3X,*SATEL3(DEG)*,3X,*THET3(DEG)*,3X,*VN(FTXFT)*,      003180
           13X,*VL(FTXFT)*,3X,*VH(FTXFT)*,//)                                     003190
            PRINT 25                                                              003200
      25    FORMAT(*T*)                                                           003210
            DO 50 I=10,90,30                                                      003220
            ED(1)=I                                                               003230
            DO 50 J=90,360,90                                                     003240
            RD(1)=J                                                               003250
            DO 50 K=10,90,30                                                      003260
            ED(2)=K                                                               003270
            DO 50 L=90,360,90                                                     003280
            RD(2)=L                                                               003290
            DO 50 M=10,90,30                                                      003300
            ED(3)=M                                                               003310
            DO 50 O=90,360,90                                                     003320
            RD(3)=O                                                               003330
            DO 30 P=1,3                                                           003340
            ER(P)=ED(P)*PI/180.0                                                  003350
            RR(P)=RD(P)*PI/180.0                                                  003360
            AX(P)=PI/2.0-ER(P)                                                    003370
```

```
      SUBROUTINE VAPPROF    74/74    OPT=1                    FTN 4.2+P388       01/17/75  08.43.46.

          AY(P)=ACOS(SIN(RR(P))*COS(ER(P)))                                   003380
          AZ(P)=ACOS(COS(RR(P))*COS(ER(P)))                                   003390
   30     CONTINUE                                                            003400
          CALL DELTAR(ER,ALT,N,DR)                                            003410
          CALL VAP(AX,AY,AZ,DR,VN,VE,VH,N,CN)                                 003420
          PRINT 40,ED(1),RD(1),ED(2),RD(2),ED(3),RD(3),VN,VE,VH               003430
   40     FORMAT(5X,F6.2,1X,F6.2,7X,F6.2,8X,F6.2,7X,F6.2,8X,F6.2,            003440
         15X,F9.3,3X,F9.3,3X,F9.3)                                            003450
   50     CONTINUE                                                            003460
          RETURN                                                              003470
          END                                                                 003480
```

```
SUBROUTINE VNCE       74/74    OPT=1                     FTN 4.2+P380       01/17/75  08.43.55.

          SUBROUTINE VNCE(ALT,THET,SATEL,N,CN)                                003490
          DIMENSION THET(3),SATEL(3),AX(3),AY(3),AZ(3),DR(3)                  003500
          REAL N                                                              003510
          PI=4.0*ATAN(1.0)                                                    003520
      ***************************************************************         003530
      *   THIS SUBROUTINE ALLOWS THE PLANNER TO CALCULATE          *         003540
      *   POSITION VARIANCES GIVEN THE USER'S ALTITUDE, THE         *         003550
      *   THREE SATELLITE ELEVATION ANGLES, AND THE POSITIVE        *         003560
      *   ANGLE FROM NORTH,THET(I), OF THE PROJECTED USER           *         003570
      *   TO SATELLITE VECTOR.                                      *         003580
      ***************************************************************         003590
          DO 10 I=1,3                                                         003600
          AX(I)=PI/2-SATEL(I)                                                 003610
          AY(I)=ACOS(SIN(THET(I))*COS(SATEL(I)))                              003620
          AZ(I)=ACOS(COS(THET(I))*COS(SATEL(I)))                              003630
     10   CONTINUE                                                            003640
          CALL DELTAR(SATEL,ALT,N,DR)                                         003650
          CALL VAR(AX,AY,AZ,DR,VN,VE,VH,CN)                                   003660
          PRINT 15,ALT                                                        003670
     15   FORMAT(//,25X,*ALTITUDE = *,F7.1,1X,*FEET*)                         003680
          DO 30 I=1,3                                                         003690
          SATEL(I)=SATEL(I)*180.0/PI                                          003700
          THET(I)=THET(I)*180.0/PI                                            003710
     30   CONTINUE                                                            003720
          PRINT 20,SATEL(1),THET(1),SATEL(2),THET(2),SATEL(3),THET(3)        003730
     20   FORMAT(/,5X,*SATEL(1) = *,F6.2,5X,*THET(1) = *,F6.2,/,             003740
         15X,*(DEGREES)*,13X,*(DEGREES)*,/,5X,*SATEL(2) = *,                  003750
         1F6.2,5X,*THET(2) = *,F6.2,/,5X,*(DEGREES)*,13X,*(DEGREES)*,         003760
         1/,5X,*SATEL(3) = *,F6.2,5X,*THET(3) = *,F6.2,/,5X,                  003770
         1*(DEGREES)*,13X,*(DEGREES)*)                                        003780
          PRINT 40,VN,VE,VH                                                   003790
     40   FORMAT(//,5X,*VN(FTXFT) = *,F9.3,5X,*VE(FTXFT) = *,F9.3,           003800
         15X,*VH(FTXFT) = *,F9.3,/)                                           003810
          RETURN                                                              003820
          END                                                                 003830
```

Appendix C

Non-ANSI List

This appendix is a listing by main program and subroutines of programing language not conforming with USA standard fortran, as defined in standard USAS X3.9-1966, of the American National Standards Institute, Inc.

```
        PROGRAM NAVSTAR    74/74    OPT=1                          FTN 4.2+P350       01/17/75  08.42.59.       PAGE      3

CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

       1   ANSI    NAVSTAR   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
       1   ANSI              THIS STATEMENT IS A NON-ANSI STATEMENT.!
      10   ANSI              THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
      19   ANSI              THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      22   ANSI              THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
      45   ANSI              THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
      46   ANSI    14 CD 46  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      46   ANSI    23 CD 46  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      46   ANSI    45 CD 46  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      46   ANSI    07 CD 47  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      46   ANSI    31 CD 47  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      48   ANSI              THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
      49   ANSI    19 CD 49  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      49   ANSI    50 CD 49  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      49   ANSI    13 CD 53  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      49   ANSI    26 CD 50  HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
      60   ANSI    VARPROF   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
      62   ANSI         20   OCCURRENCES OF ASTERISK OR DOLLAR SIGN NON-ANSI COMMENT LINES.
```

```
        SUBROUTINE DRCSNS      74/74    OPT=1                          FTN 4.2+P380       01/17/75  08.43.02.      PAGE     2

 CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

       17   ANSI                USE OF COMMENT CARD IN CONTINUED STATEMENT IS NON-ANSI.
       32   ANSI          13    OCCURRENCES OF ASTERISK OR DOLLAR SIGN NON-ANSI COMMENT LINES.
```

```
          SUBROUTINE DELTAR      74/74    OPT=1                          FTN 4.2+P380        01/17/75  08.43.04.       PAGE      2

     CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

          12    ANSI    1          THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
          12    ANSI    1          THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
          17    ANSI           5   OCCURRENCES OF ASTERISK OR DOLLAR SIGN NON-ANSI COMMENT LINES.
```

```
          SUBROUTINE VAR          74/74    OPT=1                        FTN 4.2+P380        01/17/75  08.43.19.        PAGE      2

CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

      23   ANSI          5    OCCURRENCES OF ASTERISK OR DOLLAR SIGN NON-ANSI COMMENT LINES.
```

```
      SUBROUTINE ALTEST      74/74    OPT=1                         FTN 4.2+P380        01/17/75  08.43.21.       PAGE     2

CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

      7    ANSI    PIOVER2   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
     13    ANSI    DELTASL   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
     15    ANSI    DELTASL   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
     15    ANSI    PIOVER2   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
     15    ANSI    +        THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
```

```
     SUBROUTINE PRN        74/74    OPT=1                          FTN 4.2+P380       01/17/75  08.43.29.       PAGE      3

CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

       5   ANSI    PIOVER2   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
       6   ANSI    DELTASL   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
      10   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      11   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      12   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      13   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      14   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      15   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      16   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      17   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      18   ANSI    STMT-END  THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      69   ANSI    *         THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      69   ANSI    *         THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      69   ANSI    *         THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
      92   ANSI    DELTASL   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
      92   ANSI    PIOVER2   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
      92   ANSI    PIOVER2   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
      93   ANSI    DELTASL   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
      93   ANSI    PIOVER2   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
      93   ANSI    PIOVER2   7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
     184   ANSI         37   OCCURRENCES OF ASTERISK OR DOLLAR SIGN NON-ANSI COMMENT LINES.
```

```
        SUBROUTINE VARPROF    74/74    OPT=1                          FTN 4.2+P380       01/17/75  08.43.46.       PAGE     3

CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

      1    ANSI    VARPROF    7 CHARACTER SYMBOLIC NAME IS NON-ANSI.
     24    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
     25    ANSI    14 CD 25   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
     27    ANSI    14 CD 27   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     27    ANSI    22 CD 27   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     27    ANSI    43 CD 27   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     28    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
     29    ANSI    20 CD 29   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    37 CD 29   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    53 CD 29   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    10 CD 30   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    26 CD 30   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    43 CD 30   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    59 CD 30   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    10 CD 31   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     29    ANSI    25 CD 31   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     32    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
     33    ANSI    14 CD 33   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     55    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI.SPECIFICATIONS.
     60    ANSI          18   OCCURRENCES OF ASTERISK OR DOLLAR SIGN NON-ANSI COMMENT LINES.
```

```
          SUBROUTINE VNCE       74/74    OPT=1                             FTN 4.2+P380       01/17/75  08.43.55.       PAGE     2

CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

     13    ANSI    -          THE TYPE COMBINATION OF THE OPERANDS OF A RELATIONAL OR ARITHMETIC OPERATOR (OTHER THAN **) IS NON-ANSI.
     19    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
     20    ANSI    21 CD 26   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     20    ANSI    43 CD 20   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     25    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
     26    ANSI    19 CD 26   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    41 CD 26   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    10 CD 27   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    26 CD 27   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    43 CD 27   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    15 CD 28   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    38 CD 28   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    54 CD 28   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    12 CD 29   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    34 CD 29   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    07 CD 30   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     26    ANSI    23 CD 30   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     31    ANSI               THIS FORM OF AN I/O STATEMENT DOES NOT CONFORM TO ANSI SPECIFICATIONS.
     32    ANSI    20 CD 32   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     32    ANSI    43 CD 32   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     32    ANSI    10 CD 33   HOLLERITH STRING DELINEATED BY SYMBOLS IS NON ANSI.
     35    ANSI           7   OCCURRENCES OF ASTERISK OR DOLLAR SIGN NON-ANSI COMMENT LINES.
```

VITA

John Redmond Schmidt was [redacted] [redacted] [redacted] He graduated from [redacted] PII Redacted PII Redacted [redacted], [redacted] and entered the United States Air Force Academy. He received the degree of Bachelor of Science and a commission in the USAF in 1967 and attended Undergraduate Pilot Training at Vance Air Force Base, Oklahoma. He served as a fighter pilot with the 3rd Tactical Fighter Wing and as a forward air controller with the 22nd Tactical Air Support Squadron, Bien Hoa Air Base, Republic of Viet Nam. Upon return to the United States, he flew with the 60th Flying Training Wing, Laredo Air Force Base, Texas as an instructor pilot and flight examiner. He attended the Air Force Institute of Technology where he received the degree of Master of Science in Electrical Engineering in 1975.

Permanent address: [redacted]

This thesis was typed by [redacted]

PII Redacted